# CHAPTER 3

# RADIATION

The major contributions to the energy balance of the middle atmosphere are the absorption of solar ultraviolet (or short-wave) radiation, especially by ozone, and the cooling to space through infrared (long-wave) radiation, principally by carbon dioxide. Local imbalances between short-wave heating and long-wave cooling provide the driving forces for dynamical processes. Much effort has been occurred in the past decade to accurately measure the solar irradiance in various wavelength bands and its variability on both short and long timescales. There has been good progress, although much remains to be done. Similarly, there has been steady progress in understanding of long-wave processes. The following sections summarize this progress.

## 3.1 Solar Ultraviolet Radiation

The solar electromagnetic radiation is the primary source of energy for the terrestrial environment. The largest fraction of energy associated with the solar spectrum is situated in the visible. The ultraviolet domain for wavelengths shorter than 320 nm represents only a small fraction (2 percent) of the total incident flux. This spectral range is of fundamental importance for aeronomic processes taking place in the troposphere, the middle atmosphere and the thermosphere.

Because of the complexity of the atmospheric processes and the strong interplay and feedback between transport, chemical composition and radiative budget, atmospheric and climate studies should include observations of the ultraviolet solar radiation and its variability, in close relation with the atmospheric constituent which control the penetration of solar radiation. The ozone molecule is a key minor constituent for the stratosphere by photodissociation of molecular oxygen by solar radiation of wavelengths shorter than 242nm. It provides the main heat source through the absorption of solar ultraviolet radiation and thus determines to a great extent the temperature profile in the stratosphere and the general circulation. Ozone therefore couples the stratosphere and the tropospheric climate through complex processes involving radiative, chemical and dynamical effects.

Consequently, the knowledge of solar ultraviolet irradiance values as well as their temporal variations is fundamental in studying the chemical, dynamical and radiative processes in the middle atmosphere. In addition, the study of solar variability is of crucial importance to distinguish between its impact on the terrestrial environment in comparison with anthropogenic perturbations.

During the solar cycle 21 (1975-1986), several measurements of solar ultraviolet irradiance from Lyman $\alpha$ to 400nm have been performed including observations from balloons, rockets, space shuttle and satellites. Many of those measurements have been reviewed by BRASSEUR and SIMON (1981), LEAN (1987), ROTTMAN (1987), SIMON (1978, 1981), and SIMON and BRASSEUR (1983). In addition, two WMO-NASA assessment reports on stratospheric ozone (WMO, 1982; WMO, 1986) have been published, including solar ultraviolet radiation discussions relevant to stratospheric ozone.

Variations of solar ultraviolet irradiance have also been analyzed in the same aforementioned works. More recently, new insights on the temporal variability of ultraviolet solar irradiance has been provided by DONNELLY (1988) using data acquired by the Solar Backscatter Ultraviolet (SBUV) spectrometer on board Nimbus 7 and by ROTTMAN (1989) for the data taken by the Solar Mesosphere Explorer (SME) satellite.

The following sections summarize the major findings concerning the absolute values of irradiance in wavelength bands from Lyman $\alpha$ to 320nm, and the temporal variabilities related to the 11-year solar activity cycle and the 27-day modulation, based on the observations obtained during the solar cycle 21.

## 3.2. The HI Lyman $\alpha$ Emission Line (121.6 nm)

The Lyman $\alpha$ solar chromospheric line initiates photoionization processes in the D-region and the photodissociation, for instance, of water vapor in the mesosphere, controlling the ozone budget in the mesosphere through the production of hydroxyl radicals. Two data sets have been obtained by satellite, namely the Atmospheric Explorer-E (AE-E) and SME, respectively from June 1977 to May 1980 during the rising phase of the solar cycle 21 and since January 1982 corresponding to the declining phase of the same cycle. Additional 'snapshot' observations of Lyman $\alpha$ obtained by rockets and Spacelab 2 are listed in Table 3.1.

Although some values are close to 2 x $10^{11}$ $h\nu.s^{-1}$ $cm^{-2}$ during the minimum of activity between solar cycle 20 and 21, the average value of the rocket measurements made between December 1972 and March 1977 is 3 x $10^{11}$ $h\nu.s^{-1}.cm^{-2}$. This value has been widely adopted for low solar activity condition. It has even been used as a minimum value (mid 1976) to normalize the AE-E time series. Nevertheless, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) observation which took place in August 1985 during the most recent minimum of activity gives a relatively high value of 3.79 x $10^{11}$ $h\nu.s^{-1}.cm^{-2}$, that is to say 26 percent above the conventional value adopted for minimum level of activity. However, a result quite contrary to the SUSIM value is obtained by the SME time series calibrated with a rocket observation performed on May 17, 1982 (MOUNT and ROTTMAN, 1983a) which gave minimum values around 2.5 x $10^{11}$ $h\nu.s^{-1}.cm^{-2}$ in 1986.

On the other hand, the 11-year variation range is also still uncertain. Most of the observations suggest a factor of 2 for variation over one solar cycle, except for the AE-E time series which indicates a factor of 3 but which display unexplained shifts in measured radiances for several solar emission lines. This phenomena led to criticisms of the AE-E measurements (BOSSY and NICOLET, 1982; BOSSY, 1983; OSTER, 1983). However, arguments in favor of AE-E Lyman $\alpha$ time series have also been reported by DONNELLY et al. (1986) and DONNELLY (1987). Recent analysis of the SME time series gives a variation factor of only 1.68 from January 1982 to mid 1986.

Hence, the absolute minimum value of irradiance as well as long-term variations on the activity cycle are still subject to controversy, although the reliability of SME data favors a minimum value around 2.5 x $10^{11}$ $h\nu s^{-1}cm^{-2}$ and a solar cycle variation of radiation less than a factor of two. This conclusion is supported by other studies, for instance, the data obtained by the Pioneer Venus Orbiter, suggesting a solar cycle variation of 1.8 (AJELLO et al., 1987).

The 27-day variations are well determined with the recent analysis of the SME time series since 1982 reported by SIMON et al. (1987) (see 3.6.1). This relatively large rotation effect must be considered when comparing snapshot measurements. This variation can occassionally reach a maximum of 30 percent (peak-to-peak amplitude) for the strongest 27-day modulation (e.g. August 1982) but is lower than 10 percent for a quiet Sun.

**TABLE** 3.1. Snapshot observations of the solar H I Lyman $\alpha$ emission line

| Date | Irradiance $10^{11}$ $h\nu.s^{-1}.cm^{-2}$ | Ratio flux (10.7cm) at 1 AU $10^{-22}$ $W.m.^{-2}$ $Hz^{-1}$ | Accuracy |
|---|---|---|---|
| Dec. 13, 1972 x | 3.08 | 111 | ± 23% |
| Aug. 30, 1973 x | 2.02 | 101 | ± 20% |
| Nov. 02, 1973 ° | 3.14 | 84 | ± 30% |
| Apr. 23, 1974 ° | 2.51 | 74 | ± 30% |
| Jul. 28, 1975 x | 2.20 | 76 | ± 20% |
| Feb. 18, 1976 x | 3.70 | 70 | ± 20% |
| Mar. 09, 1977 x | 4.28 | 80 | ± 20% |
| Jun. 05, 1979 + | 4.98 | 230 | ± 12% |
| Jul. 15, 1980 + | 5.50 | 218 | ± 8% |
| May. 17, 1982 + | 3.24 | 142 | ± 8% |
| Jan. 12, 1983 + | 3.01 | 135 | ± 25% |
| Jul. 25, 1983 + | 2.69 | 137 | ± 8% |
| Aug. 03, 1985 * | 3.79 | 79 | ±3.5% |

References:

° HEROUX and HIGGENS (1977) Rockets
x ROTTMAN (1981) Rockets
+ MOUNT and ROTTMAN (1985) Rockets
* VANHOOSIER AND BRUEKNER (1987), SUSIM, Spacelab 2

## 3.3 The 135-175nm Interval

This wavelength range concerns the photodissociation of molecular oxygen in the lower thermosphere and, consequently, determines the heating rate and the atomic oxygen production in that region. Much of the atomic oxygen is transported down to the mesopause and its density must be correctly known as an essential input to middle atmosphere studies. Table 3.2 gives the integrated flux between 135 and 175nm deduced from the rocket observations covering that wavelength range and from the Spacelab 2 mission, with the uncertainties quoted by the authors.

Five rocket observations made from November 1978 to December 1984 have also been reported by MENTALL et al. (1985) and MENTALL and WILLIAMS (1988). Their wavelength range for all published irradiance values starts at 150nm. All of these rocket observations relate directly to the NBS Synchroton Users Radiation Facility (SURF) calibration.

Important disagreements are still present in spite of the improvement in calibration procedures illustrated by the quoted accuracy of each observation. The two maximum values obtained in 1979 and 1980 (Table 3.2) are subject to controversy because they are not supported by the long-term variation deduced from the SME time series discussed later. On the other hand, the interpretation of dayglow measurements at 130.4nm at solar maximum requires a solar irradiance values close to those obtained during the declining phase of the solar cycle 21 (LINK et al., 1988). In addition, the differences in irradiance values cannot be explained in terms of solar rotation, because such variations do not exceed 14 percent for the CIV emission lines lying in the 150-160 nm interval, for an active Sun (SIMON et al., 1987).

Removing the 1979 and 1980 observations from the discussion, it appears that the SUSIM results obtained at a very low activity level (August 1985) with a very high quoted accuracy (±3.5 percent) give irradiance values 35 percent higher on average than the mean of four rocket observations performed between May 1982 and December 1984, corresponding to low- and moderate-activity levels.

In conclusion, the absolute value of solar irradiance between 135 and 175 nm remains uncertain and needs further correlated observations. The set of rocket measurements performed between October 1981 and December 1984 are in good agreement, with a standard deviation of only 4 percent for the 150-160 interval. The corresponding average spectrum is presented in Figure 3.1 with the SUSIM results for comparison.

## 3.4. The 175-200nm Interval

This wavelength range corresponds to the Schumann-Runge absorption bands of molecular oxygen and is directly related to its photodissociation in the mesosphere and the upper stratosphere.

Observations performed during the solar cycle 21 are listed in Table 3.3 which gives integrated values of solar irradiances over 5 and 10nm bandwidth regions with their associated accuracies. Even for the most recent measurements the divergences remain very significant, especially in the 175-180 range where the standard deviation reaches 13 percent.

Actually, this wavelength region suffers from relatively higher uncertainties than those quoted for observations made below 175nm and above 200nm, except for the SUSIM measurements. For the rocket observations, the uncertainties are between 5 and 20 percent (see Table 3.3). This may be explained by the more

TABLE 3.2. Integrated solar irradiance values between 135 and 175 nm observed since December 1972.

| Date | Radio flux at 1 AU (10.7 cm) + | Irradiance $10^{11} h\nu.s^{-1}.cm^{-2}$ | Accuracy percent | Reference |
|---|---|---|---|---|
| Dec 13 1972 | 111 | 8.7 | ± 27 | ROTTMAN (1981) |
| Aug 30 1973 | 101 | 7.7 | ± 24 | ROTTMAN (1981) |
| Nov 02 1973 | 84 | 5.7 | ± 20 | HEROUX and HIGGINS (1977) |
| Apr 23 1974 | 74 | 5.2 | ± 20 | HEROUX and HIGGENS (1977) |
| Jul 28 1975 | 76 | 8.2 | ± 24 | ROTTMAN (1981) |
| Feb 18 1976 | 70 | 10.0 | ± 24 | ROTTMAN (1981) |
| Mar 09 1977 | 80 | 10.0 | ± 24 | ROTTMAN (1981) |
| Nov 16 1978 | 129 | (8.0)* | ± 8 | MENTALL et al., (1985) |
| Jun 05 1979 | 230 | 15.0 | ± 12 | MOUNT et al., (1980) |
| May 22 1980 | 277 | (8.4)* | ± 13 | MENTALL et al., (1985) |
| Jul 15 1980 | 218 | 14.0 | ± 13 | MOUNT and ROTTMAN (1983a) |
| Oct 16 1981 | 303 | (6.7)* | ± 5 | MENTALL et al., (1985) |
| May 17 1982 | 142 | 8.0 | ± 8 | MOUNT and ROTTMAN (1983a) |
| Jul 25 1983 | 137 | 7.2 | ± 8 | MOUNT and ROTTMAN (1985) |
| AUG 3 1985 | 79 | 12.5 | ±3.5 | VANHOOSIER and BRUECKNER (1987) SUSIM, Spacelab 2 |

* From NICOLET and KENNES (1988)

Actually, values for wavelengths below 150nm were not published by MENTALL et al (1985).

+ unit: $10^{-22}$ W.m$^{-2}$ .Hz$^{-1}$.

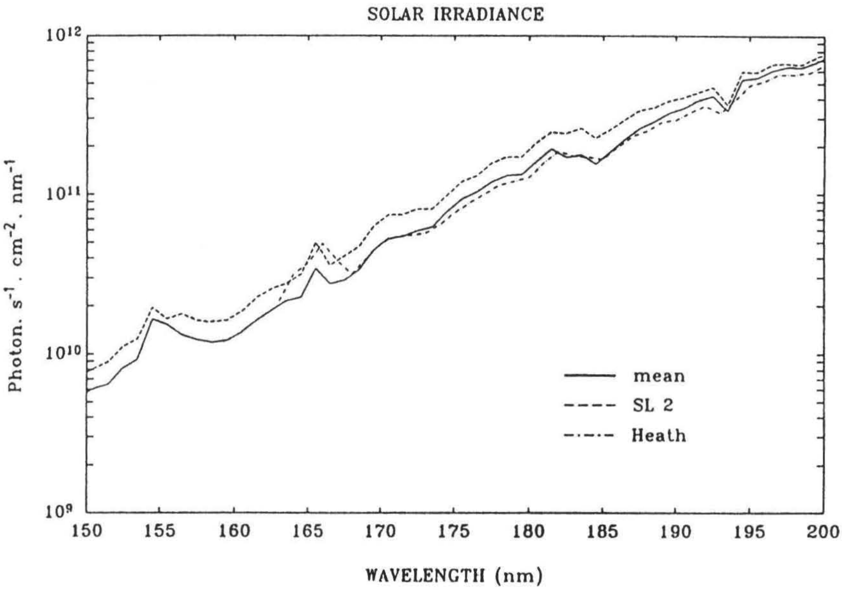


Figure 3.1 Comparison of solar ultraviolet irradiance integrated over 1nm between 150 and 200 nm. The solid curve represents the average 4 rocket observations performed between May 1982 and December 1984 (see Table 3). The dashed curve represents the data obtained from the Spacelab 2 (SL2) mission in August 1985 and the dot-dashed curve, the data reported by HEATH (1980) obtained on November 7, 1978 by SBUV.

**TABLE 3.3**

**Integrated solar irradiance values between 175 and 200 nm observed during the solar cycle 21, by means of rocket, satellite and space shuttle.**

| | Integrated irradiance (accuracy) $10^{-11}$ h.$s^{-1}$.$cm^{-2}$ (percent) | | | Solar Radio Flux $10^{-22}$ W·$m^{-2}$. $Hz^{-1}$ (1AU) | |
|---|---|---|---|---|---|
| | 275 - 180 nm | 180 - 190 nm | 190 - 200 nm | 10.7 cm | Reference |
| Nov. 07, 1978 | 5.23 (± 10%) | 20.4 (± 10%) | 46.00 (± 10%) | 175 | Heath (1980) SBUV, Nimbus 7 |
| July 15, 1980 | 7.17 (± 10%) | 22.8 (± 16%) | 49.2 (± 16%) | 218 | Mount and Rottman (1983a) |
| Oct. 16, 1981 | 5.62 (± 5%) | 23.1 (± 18%) | 44.4 (± 18%) | 303 | Mentall et al. (1985) |
| May 17, 1982 | 6.37 (± 8%) | 20.9 (± 8%) | 50.7 (± 8%) | 142 | Mount and Rottman (1983a) |
| Jan 12, 1983 | | 21.1 (± 20%) | 52.5 (± 20%) | 136 | Mount and Rottman (1983b) |
| July 25, 1983 | 5.73 (± 15%) | 20.3 (± 8%) | 50.4 (± 8%) | 137 | Mount and Rottman (1985) |
| Dec. 07, 1983 | 5.73 (± 8%) | 22.5 (± 9%) | 51.4 (± 8%) | 99 | Mentall and Williams (1988) |
| Dec. 10, 1984 | 5.44 (± 4%) | 21.8 (± 9%) | 51.8 (± 8%) | 76 | Mentall and Williams (1988) |
| Aug. 03, 1985 | 7.69 (± 3.5%) | 28.2 (± 3.5%) | 57.1 (± 3.5%) | 79 | Van Hoosier and Brueckner (1987), SUSIM, Spacelab 2 |

*Wavelength range of measured irradiance values starting at 180 nm difficult instrument calibration in this spectral range (see references listed in Table 3.3). Indeed, since the sensitivities of the two spectrometers needed to cover that spectral region are rapidly changing with wavelength, their individual calibrations are more difficult and require, in some cases, different radiometric standards. MENTALL and WILLIAMS (1988) attempt to solve this problem by using a third midrange spectrometer providing additional coverage in the overlap region (180-190 nm) of the two other instruments.

In conclusion, the absolute value of solar irradiance in the 175-200 wavelength remains very uncertain and needs further dedicated observations in order to determine accurate irradiance values for low and high activity condition.

## 3.5. The 200-320nm Interval

This spectral region is of particular interest for the stratosphere and the troposphere. Irradiance at wavelengths up to 240nm are responsible for ozone production in the stratosphere. The 280-320nm interval (UV-B) is also of fundamental importance for the tropospheric chemistry.

The 200-300 nm interval has been extensively discussed by LABS et al. (1987) when they reported the recent data obtained from the Spacelab 1 mission in December 1983. From their comparison with previous data it appears that the new data harmonize better with the spectral distributions of HEATH (1980) and MENTALL et al. (1981) than those reported by MOUNT and ROTTMAN (1983a, 1983b, 1985). However, all absolute values agree within +5 and -10 percent.

The most recent observations, performed during the Spacelab 2 mission by means of the SUSIM experiment and reported by VANHOOSIER and BRUECKNER (1987), are in very good agreement with the Spacelab 1 data beyond 220nm, namely within ±2 percent, but diverge by 14 percent at 200nm. The comparison of the Spacelab 1 data with those of MENTALL and WILLIAMS, (1988) obtained by rocket gives divergences up to 11 percent at 200nm but decreases to less than 4 percent between 260 and 310nm. It should bepointed out that the new rocket measurements refer to identical spectrometers and to similar calibration procedures traceable to the NBS radiometric scale. The average spectrum is given in Figure 3.2.

The ratios of irradiances referred to the Spacelab 1 data are presented in Figure 3.3 for the different observations. As far as the absolute value is concerned, nearly all values agree within ± 10 percent. The quoted accuracy of the Spacelab 1 and Spacelab 2 observations are respectively 5.2 percent and 3.5 percent.

## 3.6. Temporal Variations of Solar Ultraviolet

The ultraviolet range of the solar electromagnetic spectrum is characterized by its temporal variations which directly affect the atmosphere. Two time scales are generally considered in relation with aeronomic studies of the middle atmosphere: the 11-year activity cycle and the 27-day rotation period of the Sun. At present, effects of long-term variation of solar ultraviolet irradiance are not conclusive because observations of changes on that time scale in both the ultraviolet solar flux and the sensitive trace species are not reliable at the level of natural changes.

Because of the difficulty in detecting the solar irradiance variation related to the solar activity cycle, the impact of the 27-day variation associated with the rotation period of the Sun was analyzed in detail. Indeed, observations over short scale periods are far more accurate in that they avoid the aging

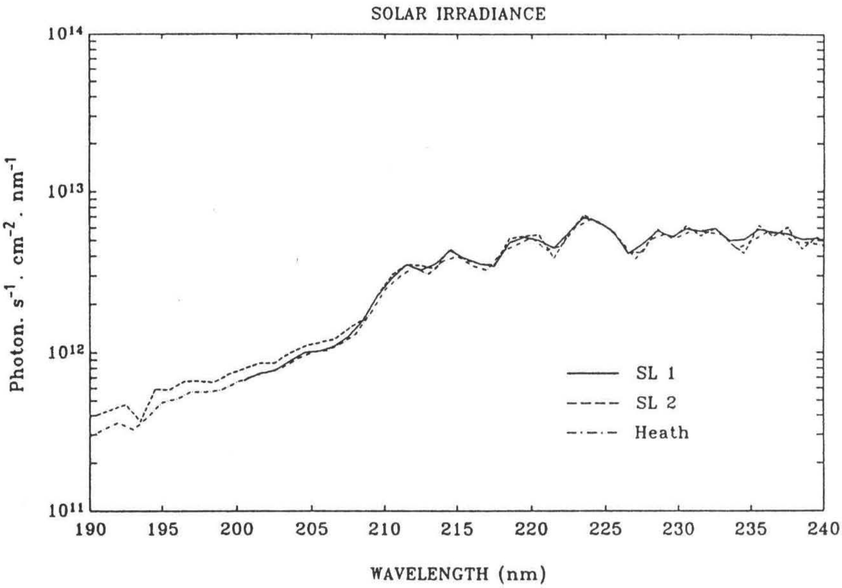


Figure 3.2 Comparison of solar ultraviolet irradiance integrated over 1nm between 190 and 240 nm. The solid curve represents the data obtained from the Spacelab 1 (SL1) mission in December 1984. The dashed curve represents the data obtained from the Spacelab 2 (SL2) mission in August 1985, and the dot-dashed curve, the data reported by HEATH (1980) obtained on November 7, 1978 from SBUV.

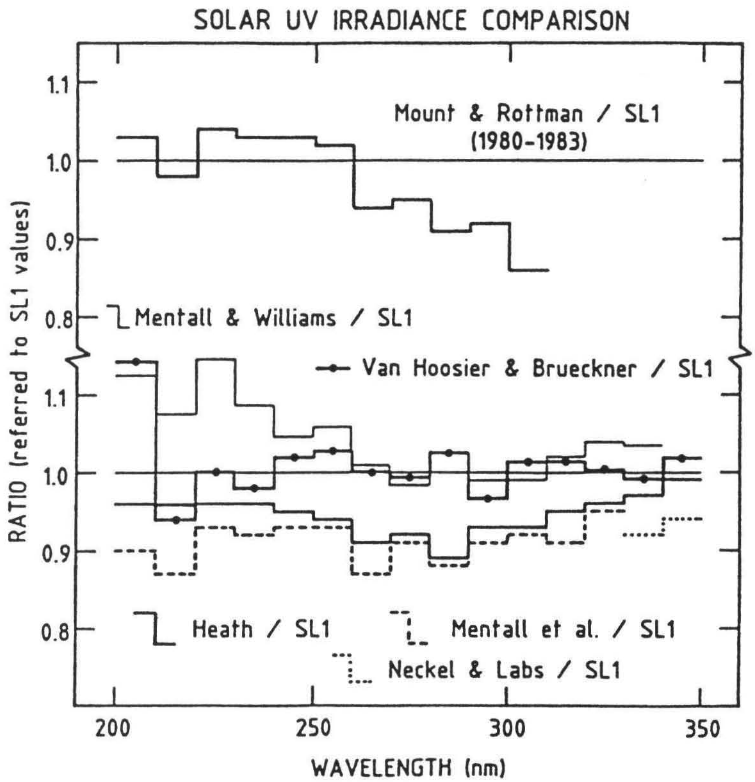


Figure 3.3 Comparison of 10 nm spectral averages of solar irradiances measurements between 200 and 350 nm with the Spacelab 1 (SL1) results (adapted from LABS et al., 1987).

problem of the observing instrumentation. These studies are very useful in the validation of photochemical processes.

### 3.6.1 The 27-Day Variations

The 27-day solar rotation variations have been well documented with the SBUV satellite and the SME data base. The analysis of solar-rotation induced variations from the SBUV observations has been recently reported by Donnelly (1988) showing great uniformity in the shape of this modulation during the six years of observation from November 7, 1978 to October 29, 1984 for wavelengths between 175 and 285nm. Several examples of variations in that spectral region have been published by HEATH and SCHLESINGER (1986). The strongest modulation occurred in August 1982, giving a variation of 6 percent at 205 nm.

The SME data base has also been extensively analyzed using the Fast Fourier Transform technique (FFT) to isolate the solar flux modulation related to the 27-day solar rotation. The amplitude variations over the full spectral range, namely 115-300nm, have been deduced for five years of observation from January 1, 1982 to December 31, 1986. The first results of this analysis have been reported by SIMON et al. (1987). An example of the temporal variations of the peak-to-peak amplitude for modulation at Lyman $\alpha$ and 205nm is presented in Figure 3.4. These 27-day modulations show periods of high uniformity in shape as, for example, in mid-1982. On the other hand, other periods show striking differences in shape for those two wavelengths as, for instance, in mid-1983 and the beginning of 1984.

The same technique has been applied to the SBUV time series for comparison purposes. The agreement between the two satellites during the overlapping period of time is very good for the strongest modulation which took place in August 1982 as illustrated in Figure 3.5. However, the average during the declining phase of the solar cycle shows some appreciable differences beyond 240nm where SBUV data are less noisy than those of SME and below 190nm where SME give higher 27-day variations than SBUV, especially for the Si II lines. The agreement is very good for wavelengths between 210 and 230nm. The best description of the 27-day variations during the declining phase of solar cycle 21 would be provided by the SME data base from 115 to 210 and from the SBUV observation from 210 to 300nm.

### 3.6.2. Solar Cycle Variations

Despite of considerable observational effort during the last cycle, the amplitude of solar variation associated with the 11-year activity cycle is still uncertain. The SBUV spectrometer suffered from severe aging problems, mainly in the reflectivity of the diffuser plate used for solar irradiance measurements. The available data have been accordingly corrected for instrument related changes (DONNELLY, 1988) and were analyzed by HEATH and SCHLESINGER (1986). They deduced long-term variations from an empirical relation based on temporal variation of ratios between core and wings irradiances of the Mg II lines at 280nm. This study is intended to eliminate the effects of instrumental drift and defines the so-called Mg II index. Balloon measurements at high resolution reported by HALL and ANDERSON (1988) demonstrate that the value of the Mg II index is very sensitive to unique instruments characteristics (spectral bandpass and line shape). Consequently, the extension of this index to other data sets has to be made very carefully and requires a critical normalization with data overlapping in time with SBUV observations. On the other hand, the amplitude of the solar cycle variations deduced from the Mg II index are not fully confirmed by the SME results obtained during the declining phase of solar cycle 21 (since 1982) which lead to lower values in the overlapping wavelength range (160-300nm). In addition, long-term variations

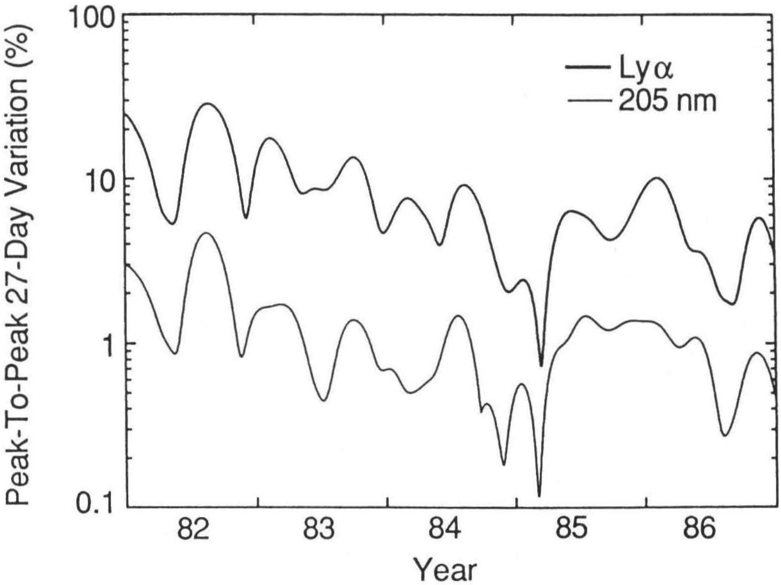


Figure 3.4 Temporal variations, deduced from a FFT analysis of the SME data of the 27-day peak-to-peak amplitude of the solar-rotation induced modulation between January 1982 and December 1986, at 2 wavelengths, namely Lyman $\alpha$ (thick curve) and 205nm (thin curve).

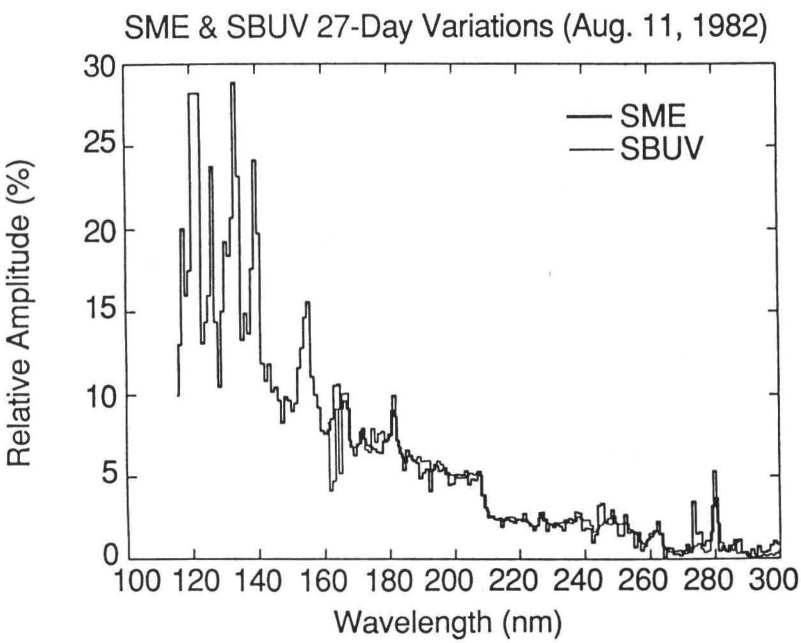


Figure 3.5 Comparison of the peak-to-peak amplitude for the 27-day variation deduced from SME (thick curve) and SBUV (thin curve) observations as a function of wavelength for 1nm intervals, for a major variation on August 11, 1982.

between 115 and 180nm deduced by comparison between rocket observations made during maximum levels of solar activity, namely 1979 and 1980 (MOUNT et al., 1980; MOUNT and ROTTMAN, 1981) and those performed at solar minimum (ROTTMAN, 1981), were of the order of 2 for Lyman $\alpha$, as well as around a wavelength of 150nm. These high values are not supported by recent analysis of SME data, which imply variations of only 15 percent around 150nm and of 5 percent between 180 and 210nm (Figure 3.6).

## 3.7. Conclusions

Knowledge of solar ultraviolet irradiance was very poor until 1981. Uncertainties in observations varied between 10 and 20 percent for most of the published irradiance measurements performed from space (SIMON, 1978; SIMON, 1981). In addition, their divergencies were larger than the quoted accuracies and much larger than the accuracies of calibration sources used at that time.

Considering that radiometric transfer sources available in 1980 had uncertainties varying from about 6 percent near 165nm to 3 percent near 400nm, the accuracies of solar irradiances measurements were expected to be in the same range. The discrepancies at that time between the accuracy goals and the achieved uncertainties for the data actually approached factors of 2 to 7 depending upon wavelength range and instrumentation. At that time, the Synchroton Users Radiation Facility (SURF) was not yet used for the calibration of published solar irradiance observations. More recent rocket observations obtained during the 1980s by the Goddard Space Flight Center (GSFC) and the Laboratory for Atmospheric and Space Physics (LASP) have been calibrated by using the NBS SURF radiometric standard. This important step forward in the calibration procedure immediately reduced the data uncertainties to ±8 percent (see the error budget in MOUNT and ROTTMAN, 1983a).

On the other hand, in-flight calibration sources have been developed for the Spacelab 1 and 2 experiments, namely the "Solar Spectrum" and "Solar Ultraviolet Spectral Irradiance Monitor" (SUSIM). They have reported new data referenced respectively to the black body of the Heidelberg Observatory (LABS et al., 1987) and to the SURF (VANHOOSIER and BRUECKNER, 1987). Irradiance values are now available with an accuracy from 3.5 percent (SUSIM) to 5.2 percent (Solar Spectrum).

In spite of the improvements in calibration procedures, important discrepancies persist between recent irradiance measurements in the spectral range between Lyman $\alpha$ and 200nm. This fact is probably explained by experimental problems encountered in that spectral domain. Basic questions, for instance the minimum value of Lyman $\alpha$ irradiance, still need to be correctly addressed in the next decade.

If the 27-day variations are well documented with the SBUV and SME observations during the solar cycle 21, the long-term variations related to the solar activity still remain uncertain. This is due to large differences between many measurements performed from 1977 to 1985. Nevertheless, good arguments now seem to validate the proposed solar cycle variation deduced from SME. This problem is of fundamental importance in ozone trend studies. Indeed, predictions in total ozone changes during the current solar cycle (its maximum of activity being expected in 1991) give an increase of ozone towards a maximum at that time. This means that the solar cycle variation in ultraviolet irradiance will counterbalance the predicted decrease due to anthropogenic chlorine compound emissions. After 1991, the total ozone column is predicted to decrease again with a rate still enhanced by the decline in solar ultraviolet irradiance. Consequently, reliable observations of solar variation with a precision of 1

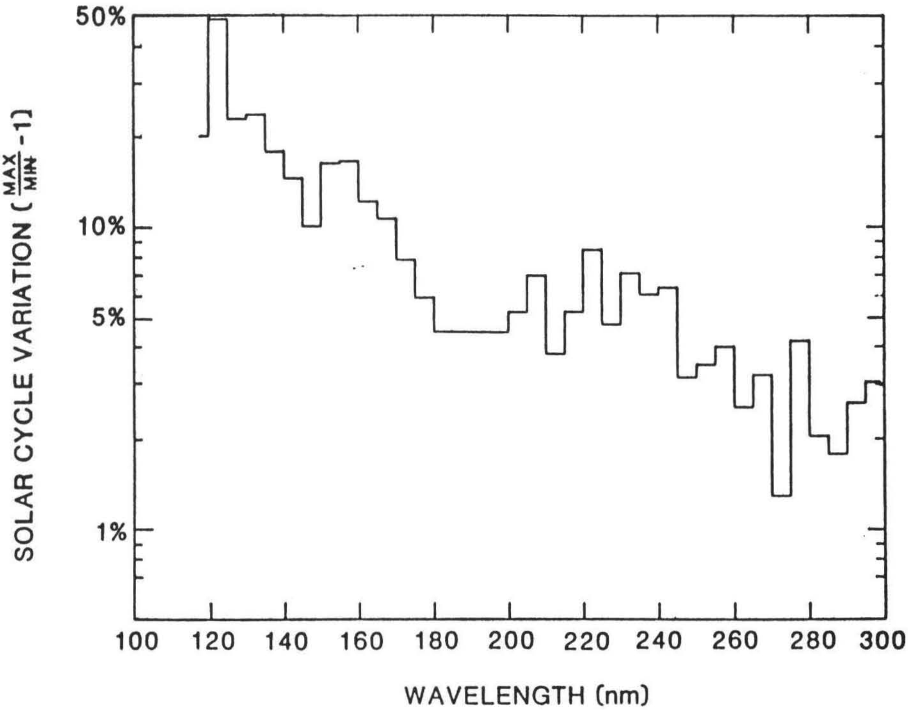


Figure 3.6 Preliminary solar cycle variation between 1982 and 1985 deduced from the SME measurements integrated over 5nm intervals between 125 and 300nm (1nm intervals). Error bars might be as large as a factor of 2 beyond 200nm (from ROTTMAN, 1989).

percent over a half solar cycle are urgently needed to quantitatively discriminate between natural changes and anthropogenic perturbations in the middle atmosphere composition.

## 3.8 The Role of Longwave Radiative Processes

Longwave radiation is generally defined as that part of the electromagnetic spectrum lying between 4 and approximately 200 microns. The most radiatively active atmospheric constituents for this part of the spectrum are carbon dioxide, ozone, and water vapor. In the middle atmosphere, these gases contribute to a net cooling. The longwave radiative cooling process differs from the shortwave radiative process in two important ways. First, the cooling at a particular altitude depends upon the exchange of radiation with the atmospheric layers both above and below this region. Thus, longwave cooling is coupled to regions far from the point of interest. Second, longwave cooling depends strongly on the atmospheric temperature. These two unique aspects of the longwave cooling process lead to a number of important consequences for middle atmosphere research. In particular, the temperature dependence implies that longwave cooling acts as a damping agent to temperature deviations. Thus, longwave cooling is an important dissapative source in the middle atmosphere. Secondly, the exchange aspect of longwave cooling implies that coupling between the upper troposphere and the lower stratosphere can be important. Coupling of the mesosphere to the stratosphere can also occur through this exchange of radiation.

To gain insight into the required accuracy of longwave cooling rates in the stratosphere, two factors can be considered. First, the error of the thermal structure, $\Delta T$, of the stratosphere can be related to uncertainties in the net radiative cooling, $\Delta Q$, through (FELS et al., 1980).

$$\Delta T = \tau_r \, \Delta Q$$

where $\tau_r$ is the radiative relaxation time in days. For the upper stratosphere $\tau_r$ is approximately 5 days, while in the lower stratosphere it can be as large as 80 days. If it is assumed that errors in longwave cooling dominate the uncertainties in the solar heating, then errors in the temperature field of less than 5K require an accuracy in the longwave cooling rate in the upper stratosphere of around 1 K day$^{-1}$ and less than 0.07 K day$^{-1}$ in the lower stratosphere! This example sensitivity of the lower stratosphere to errors in radiative cooling. As it turns out the contribution of each gas to the cooling in the lower stratosphere is small, and hence each component of the total cooling rate must be calculated to great accuracy.

Another way to estimate the required accuracy of radiative cooling rates in the middle atmosphere is to consider the problem of transport of chemical species. Assuming the true Lagrangian circulation can be represented by the transformed Eularian mean (TEM) circulation (DUNKERTON, 1978). The TEM vertical velocity is,

$$\bar{w}^* = \frac{Q}{N^2 H R^{-1}}$$

where $N^2$ is the square of the buoyancy frequency, H is the scale height, R is the gas constant, and Q is the net radiative cooling in K day$^{-1}$. Typical middle atmosphere values for these constants yield.

$$w^* = 0.1 \text{ Q cm s}^{-1}$$

Once again it is assumed that the largest errors arise from longwave process. Vertical velocities in the lower stratosphere are less than 0.05 cm s$^{-1}$ (SOLOMON et al., 1986). Thus, if the required accuracy in the vertical velocity is to be less than 0.02 cm $s^{-1}$ for the lower stratosphere, than the cooling rates must be known to better than 0.2 K $day^{-1}$.

These estimates indicate that more accuracy is required in the lower stratosphere than in the upper stratosphere. Unfortunately, this is exactly the region of the stratosphere where cooling rates are most difficult to calculate. This is mainly due to the fact that each gas contributes a small and equal magnitude effect to the total cooling; and that exchange with the troposphere plays a major role in the cooling of the lower stratosphere.

The calculation of mesospheric cooling rates is dominated by two additional complications. First, pressures are sufficiently low that collisionally broadend lines (i.e. Lorentzian lines) are replaced by a Voigt line shape. Fast and accurate evaluations of the Voigt line profile are thus required for cooling rate calculations. More importantly, at altitudes above approximately 75km, non-local thermodynamic equilibrium (NLTE) becomes evident. This arises because of fewer collisions between molecules than occur at lower altitudes. With fewer collisions available to de-excite the molecules, other processes of de-excitation must be considered. Account must be taken of exchange of energy with other molecules or isotopes of the same molecule. Solution of the mesospheric cooling rates, therefore, depends on knowledge of not only spectroscopic line parameters of a given molecule, but of energy transfer rates between one type of molecule and surrounding species.

## 3.9 Advances in Middle Atmosphere Longwave Radiation

Over the past decade a number of advances have occurred in our understanding of middle atmosphere longwave radiation processes. These include: diagnostic studies of the radiative balance of the middle atmosphere, benchmark line-by-line cooling rate calculations, the effects of cirrus and polar stratospheric clouds on stratospheric radiative cooling, and more detailed budget studies of the mesosphere.

Diagnostic studies of the radiative balance of the middle atmosphere employ observed profiles of temperature, ozone and water vapor in conjunction with detailed radiation models. A number of studies on the radiative budget have appeared in the last 2 years (KIEHL and SOLOMON, 1986, GILLE and LYJAK, 1986, ROSENFIELD et al., 1987, CALLIS et al., 1987). These studies have used differing input data sources and radiation models. Thus, it is no surprise that important differences do exist among the studies. Results from one of these studies (KIEHL and SOLOMON, 1986) are used to indicate the relative contribution of the various gases to the longwave cooling of the middle atmosphere (see figure 3.7a-c). Carbon dioxide is the major contributor to longwave cooling. Ozone cools the upper stratosphere, but actually warms the lower tropical stratosphere. This warming results from the exchange of radiation between the troposphere and the lower stratosphere. Water vapor contributes a non-negligible cooling of 1 K $day^{-1}$ near the summer stratopause region. The total longwave cooling is shown in figure 3.8. It is important to note that a number of other $CO_2$ bands contribute to the net cooling of the middle atmosphere. Additional cooling also arises from trace gases such as methane and nitrous oxide.

Over the last 4 years an intercomparison of radiation codes used in climate models (ICRCCM) has taken place. A number of line-by-line model calculations were performed for this intercomparison. Unfortunately, the profiles used for these studies emphasized the troposphere. However, accurate estimates of stratospheric cooling rates are available from the line-by-line community for a small set of profiles. These line-by-line cooling rates now provide benchmarks

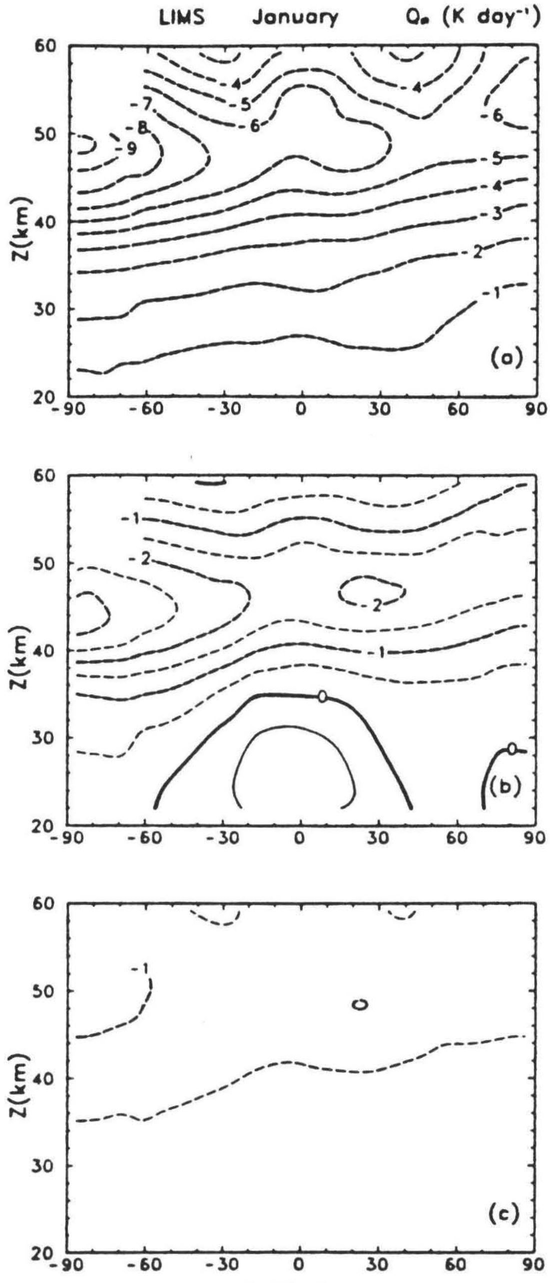


Figure 3.7 Longwave cooling due to $CO_2$ a), $O_3$ b) and $H_2O$ c) from KIEHL and SOLOMON (1986)

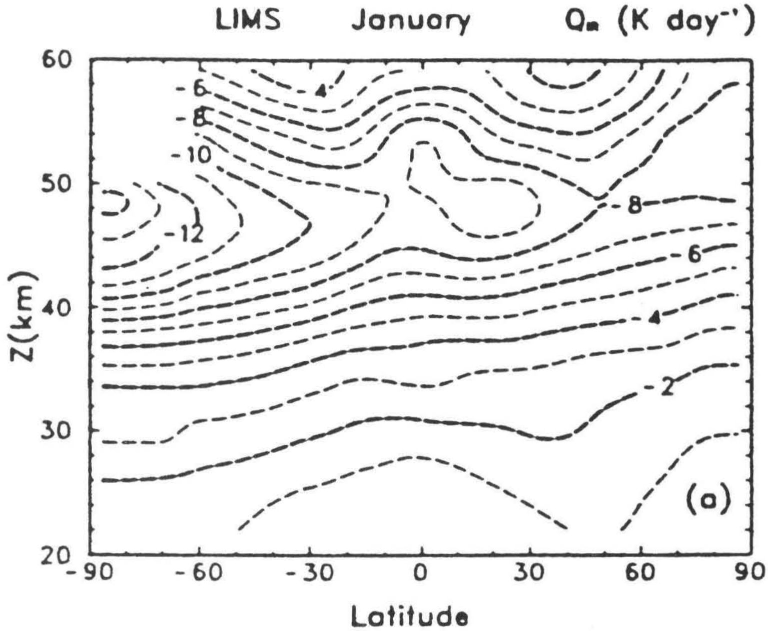


Figure 3.8 Total longwave cooling due to all gases from KIEHL and SOLOMON (1986).

to compare more parameterized models of the longwave radiative transfer process.

As noted in figure 3.7c there is a significant coupling of the tropical troposphere to the lower stratosphere. The presence of cirrus clouds can alter to a large extent the amount of longwave radiation exiting the troposphere and entering the lower stratosphere. For example, the presence of high cirrus clouds can increase the cooling of the lower stratosphere by 0.2 K $day^{-1}$. This is a significant change since it is of the same order as the estimates of acceptable error for this region of the middle atmosphere. Polar stratospheric clouds are now viewed as important to the chemical processes in the stratosphere. It is not clear at present whether they also play a non-negligible role in the radiative budget of the polar lower stratosphere. The damping properties of longwave radiation in the stratosphere and the mesosphere have more recently been studied by FELS (1982, 1984), respectively. These studies provide simple parameterizations of the damping rate as a function of the altitude and vertical scale of the temperature perturbation. Results for the stratosphere are shown in figure 3.9. It is apparent that for the middle and upper stratosphere damping rates are strongly scale dependent for the shorter scale waves (~6 to 12km). Since waves of this scale are known to exist in the equatorial middle atmosphere it is important that this scale dependence be accounted for in studies of their vertical propagation in the middle atmosphere.

The past 10 years has also witnessed advances in mesospheric longwave radiation studies. DICKINSON (1984, 1986) has discussed the major problems facing this field of research. Figure 3.10 shows longwave rates (DICKINSON, 1984) for the middle stratosphere through the mesosphere. The most difficult region to model lies between 70 and 90km. It is in this region that the cooling rates are strongly influenced by exchange with layers above and below. A significant amount of exchange takes place in the isotopic and hot bands of the $CO_2$ molecule. The importance of exchange for the fundamental $CO_2$ band is indicated in figure 3.11 where the ratio of layer exchange to cool-to-space contributions to the longwave cooling are shown. Note in particular the extreme importance of the exchange process for the summer mesopause region. Above 80km the cooling by $CO_2$ depends on the reaction of $CO_2$ with molecular oxygen. The reaction rate for this process is currently poorly known at present. Until this reaction rate is measured to higher accuracy, cooling above 80km will remain largely uncertain.

Recommendations

(1) Most of the solar ultraviolet radiation is absorbed in the middle atmosphere and the structure of this region is very sensitive to small changes in solar output. It is crucial that measurements of absolute values of irradiance are addressed. Measurements with a precision of 1 percent over a solar cycle are urgently needed in order to resolve the origins of change caused by natural and anthropenic perturbations of the middle atmosphere.

(2) A global compilation of temperatures, ozone amounts and water vapor mixing ratios for the middle atmosphere are required for future radiative balance studies. Along with this, more information on the height and extent of tropical cirrus clouds is required for accurate estimates of the radiative budget of the lower stratosphere. Needed also are the radiative properties of the cirrus clouds.

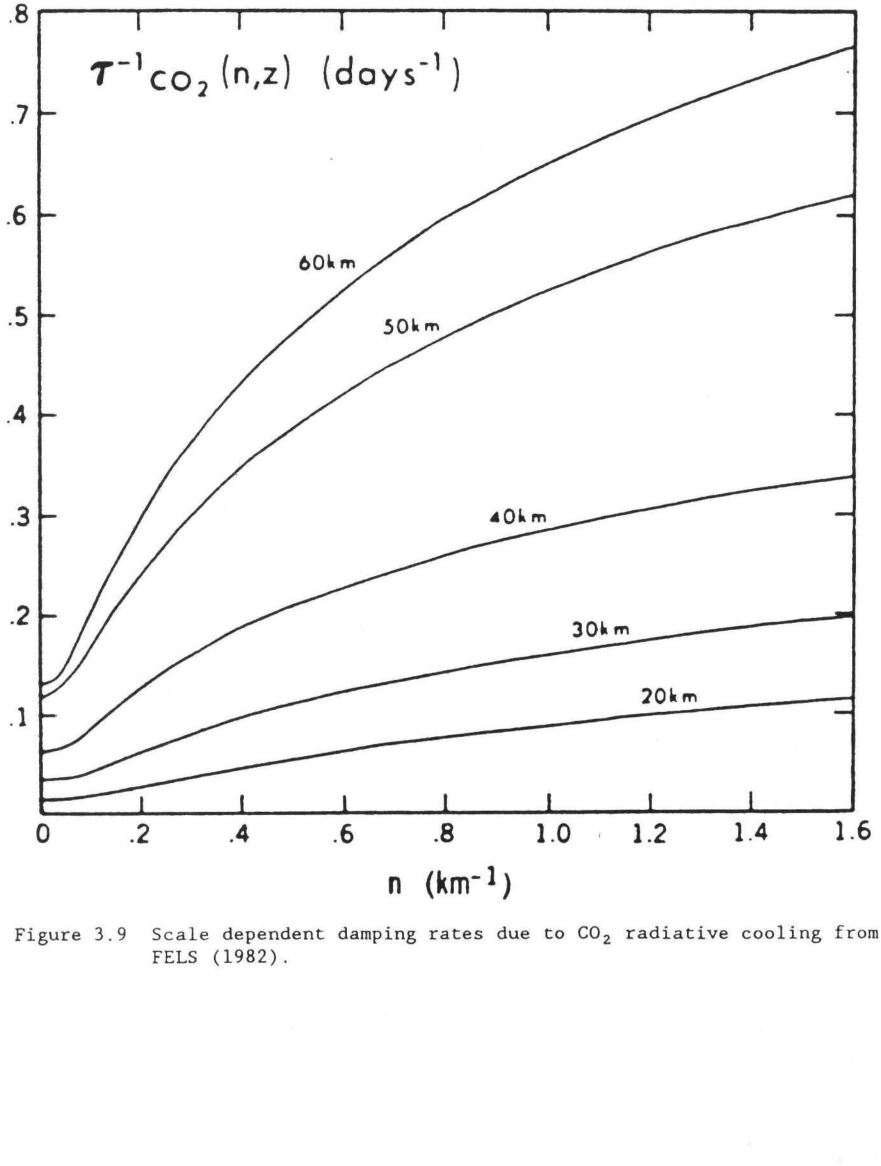


Figure 3.9 Scale dependent damping rates due to $CO_2$ radiative cooling from FELS (1982).

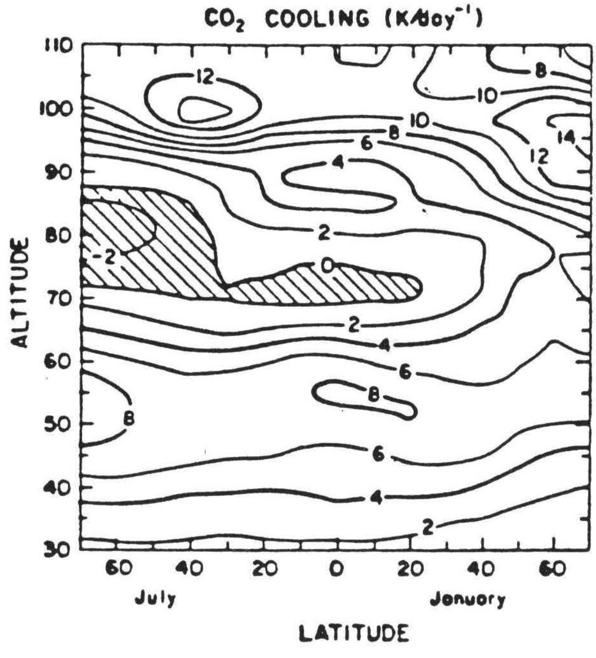


Figure 3.10 Mesospheric cooling rates calculated by DICKINSON (1984). NLTE effects are accounted for in the cooling.

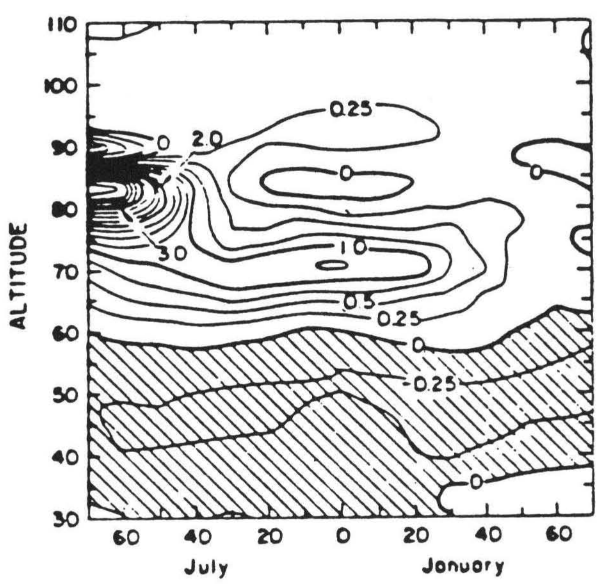


Figure 3.11 Ratio of cooling due to exchange processes to cool-to-space cooling. Results are from DICKINSON (1984).

(3) A more comprehensive set of line-by-line calculations for middle atmospheric cooling rates is needed. Also, a detailed calculation of the radiative contribution of trace gases and minor bands of $CO_2$ and $O_3$ are needed.

(4) The radiative effects of polar stratospheric clouds must be studied in greater detail. The importance of these clouds to chemical reactions is now recognized. Their radiative role remains undefined at present.

(5) More detailed knowledge of spectral line shapes and their temperature dependence is required. This is required especially for $CO_2$, where the line shape is known to deviate from the Lorentzian shape in the far wings.

(6) Radiative cooling rate calculations in the upper mesosphere require a more accurate determination of the reaction between $CO_2$ and molecular oxygen. Laboratory studies should be carried out that better define this rate.